Functional Programming in C++11

science + computing ag
IT-Dienstleistungen und Software für anspruchsvolle Rechnernetze
Tübingen | München | Berlin | Düsseldorf

An Overview

- Programming in a functional style
- Why functional programming?
- What is functional programming?
- Characteristics of functional programming
  - first-class functions
  - higher-order functions
  - pure functions
  - recursion
  - list processing
  - lazy evaluation
- What's missing?

Programming in a functional style

- Automatic type deduction with
  - auto and decltype
- Support for lambda-functions
  - closures
  - functions as data
- Partial function application
  - std::function and std::bind
  - lambda-functions and auto
- Higher-order functions in the algorithms of the STL
- *List manipulation* with variadic templates
- Pattern matching with full and partial template specialisation
- Lazy evaluation with std::async
- Constrained templates (concepts) will be part of C++1y.

Why functional programming?

- Standard Template Library (STL)
  - more effective use with lambda-functions

```
accumulate(vec.begin(),vec.end(),
           [](int a,int b){return a+b;});
```

- Template Programming
  - recognizing functional patterns

```
template <int N>
struct Fac{ static int const val= N * Fac<N-1>::val; };
template <>
struct Fac<0>{ static int const val= 1; };
```

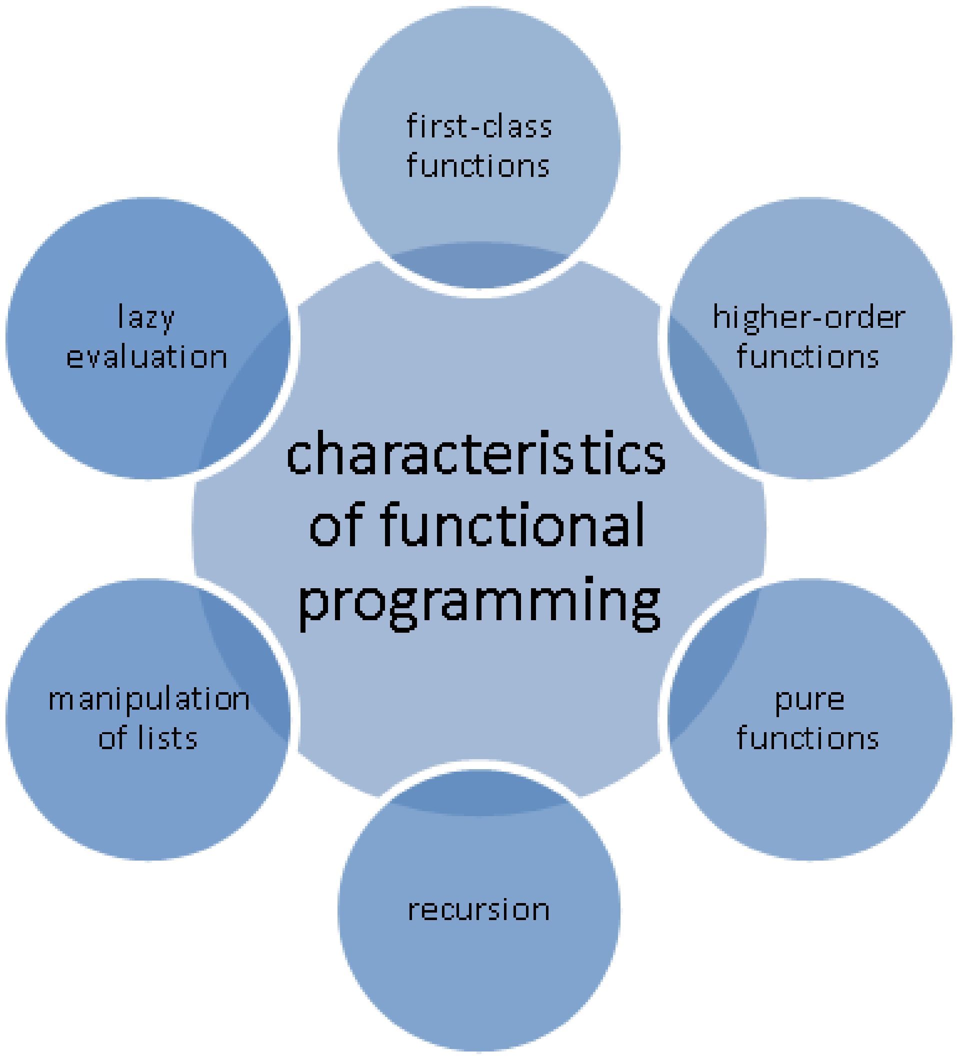
- Better programming style
  - reasoning about side effects
  - more concise

```
for (auto v: vec) cout << v << " " << endl;
```

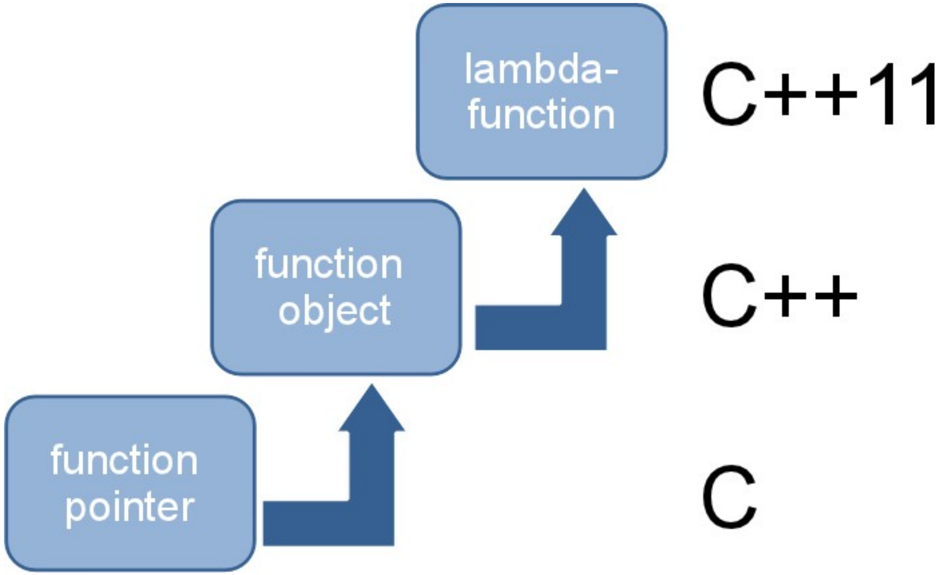
What is functional programming?

- **Functional programming** is programming with mathematical functions.
- **Mathematical functions** are functions that each time return the same value when given the same arguments (referencial transparency).
  - Functions are not allowed to have side effects.
  - The function invocation can be replaced by the result.
  - The optimizer is allowed to rearrange the function invocations or he can perform the function invocation on a different thread.
  - The program flow will be driven by the data dependencies and not by the sequence of instructions.

Characteristics of functional programming



First-class functions



- First-class functions are first-class citizens.
  - ➜ Functions are like data.
- Functions
  - can be passed as arguments to other functions.
  - can be returned from other functions.
  - can be assigned to variables or stored in a data structure.

First-class functions: dispatch table

```
map<const char,function<double(double,double)>>  tab;

tab.insert(make_pair('+',[](double a,double b){return a + b;}));
tab.insert(make_pair('-',[](double a,double b){return a - b;}));
tab.insert(make_pair('*',[](double a,double b){return a * b;}));
tab.insert(make_pair('/',[](double a,double b){return a / b;}));


cout << "3.5+4.5= " << tab['+'](3.5,4.5) << endl;    // 8
cout << "3.5*4.5= " << tab['*'](3.5,4.5) << endl;    // 15.75

tab.insert(make_pair('^',
                    [](double a,double b){return pow(a,b);}));
cout << "3.5^4.5= " << tab['^'](3.5,4.5) << endl;    // 280.741
```

Higher-order functions

- Higher-order functions are functions that accept other functions as argument or return them as result.

(source: http://musicantic.blogspot.de, 2012-10-16)

- The three classics:
  - **map**:
    Apply a function to each element of a list.
  - **filter**:
    Remove elements from a list.
  - **fold**:
    Reduce a list to a single value by successively applying a binary operation.

Higher-order functions

- Each programming language supporting programming in a functional style offers **map**, **filter** and **fold.**

Haskell	Python	C++
map	map	std::transform
filter	filter	std::remove_if
fold*	reduce	std::accumulate

- **map**, **filter** and **fold** are 3 powerful functions which are applicable in many cases.
  - map + reduce= MapReduce

Higher-order functions

- Lists and vectors:
  - Haskell:

```
vec= [1 . . 9]
str= ["Programming","in","a","functional","style."]
```

  - Python:

```
vec=range(1,10)
str=["Programming","in","a","functional","style."]
```

  - C++11:

```
vector<int> vec{1,2,3,4,5,6,7,8,9}
vector<string>str{"Programming","in","a","functional",
                  "style."}
```

- The results will be displayed in Haskell or Python notation.

Higher-order functions

science + computing
A Bull Group Company

- map
  - Haskell:

```
map(\a → a^2) vec
map(\a -> length a) str
```

  - Python:

```
map(lambda x :  x*x , vec)
map(lambda x : len(x),str)
```

  - C++11:

```
transform(vec.begin(),vec.end(),vec.begin(),
          [](int i){ return i*i; });
transform(str.begin(),str.end(),back_inserter(vec2),
          [](string s){ return s.length(); });
```

➔ Results: [1,4,9,16,25,36,49,64,81]
[11,2,1,10,6]

Higher-order functions

- filter
  - Haskell:

```
filter(\x-> x<3 || x>8) vec

filter(\x → isUpper(head x)) str
```

  - Python:

```
filter(lambda x: x<3 or x>8 , vec)

filter(lambda x: x[0].isupper(),str)
```

  - C++11:

```
auto it= remove_if(vec.begin(),vec.end(),
         [](int i){ return !((i < 3) or (i > 8)) });

auto it2= remove_if(str.begin(),str.end(),
          [](string s){ return !(isupper(s[0])); });
```

➔ Results: [1,2,9] and [“Programming”]

Higher-order functions

- fold
  - Haskell:

```
foldl (\a b → a * b) 1 vec
foldl (\a b → a ++ ":" ++ b ) "" str
```

  - Python:

```
reduce(lambda a , b: a * b, vec, 1)
reduce(lambda a, b: a + b, str,"")
```

  - C++11:

```
accumulate(vec.begin(),vec.end(),1,
           [](int a, int b){ return a*b; });
accumulate(str.begin(),str.end(),string(""),
           [](string a,string b){ return a+":"+b; });
```

➜ Results: 362800 and ":Programming:in:a:functional:style."

Pure functions

- Pure versus impure functions (from the book Real World Haskell)

pure functions	impure functions
Always produces the same result when given the same parameters.	May produce different results for the same parameters.
Never have side effects.	May have side effects.
Never alter state.	May alter the global state of the program, system, or world.

- Pure functions are isolated. The program is easier to
  - reason about.
  - refactor and test.
- Great opportunity for optimization
  - Saving results of pure function invocations
  - Reordering pure function invocations or performing them on other threads

Pure functions

- Monads are the Haskell solution to deal with the impure world.
- A Monad
  - encapsulates the impure world in pure Haskell.
  - is a imperative subsystem in Haskell.
  - is a structure which represents computation.
  - has to define the composition of computations.
- Examples:
  - I/O monad for dealing with input and output
  - Maybe monad for computations that can fail
  - List monad for computations with zero or more valid answers
  - State monad for representing stateful computation
  - STM monad for software transactional memory

Recursion

```
Fac<5>::value =
                = 5 * Fac<4>::value
                = 5 * 4  * Fac<3>::value
                = 5 * 4 * 3 * Fac<2>::value
                = 5 * 4 * 3 * 2 * Fac<1>::value
                = 5 * 4 * 3 * 2 * 1 *  Fac<0>::value
                = 120
```

- Loops:
  - Recursion is the control structure.
  - A loop `(for int i=0; i <= 0; ++i)` needs a variable `i`.
    - ➔ Mutable variables are not known in functional languages like Haskell.
- Recursion combined with list processing is a powerful pattern in functional languages.

Recursion

- Haskell:

```
fac 0= 1
fac n= n * fac (n-1)
```

- C++:

```
template<int N>
struct Fac{
  static int const value= N * Fac<N-1>::value;
};

template <>
struct Fac<0>{
  static int const value = 1;
};
```

  - Result: fac(5) == Fac<5>::value == 120

List processing

- LISt Processing is the characteristic for functional programming:
  - transforming a list into another list
  - reducing a list to a value
- The functional pattern for list processing:
  1) Processing the head (`x`) of the list
  2) Recursively processing the tail (`xs`) of the list => Go to step 1).
  - Examples:

```
mySum []      = 0
mySum (x:xs) = x + mySum xs
mySum [1,2,3,4,5]                      // 15
myMap f [] = []
myMap f (x:xs)= f x: myMap f xs
myMap (\x → x*x)[1,2,3]                // [1,4,9]
```

List processing

```
template<int ...> struct mySum;

template<>struct
mySum<>{
  static const int value= 0;
};

template<int i, int ... tail> struct
mySum<i,tail...>{
  static const int value= i + mySum<tail...>::value;
};
int sum= mySum<1,2,3,4,5>::value;            // sum == 15
```

- You do not really want to implement `myMap` with variadic templates.
  (http://www.linux-magazin.de/Heft-Abo/Ausgaben/2011/01/C/%28offset%29/2)

List processing

- The key idea behind list processing is pattern matching.
  - First match in Haskell

```
mult n 0 = 0
mult n 1 = n
mult n m = (mult n (m – 1)) + n
```

    - Example:

```
mult 3 2 = (mult 3 (2 – 1)) + 3
         = (mult 3 1 ) + 3
         = 3 + 3
         = 6
```

  - Best match in C++11

```
template < int N1, int N2 > class Mult { … };
template < int N1 > class Mult <N1,1> { … };
template < int N1 > class Mult <N1,0> { … };
```

Lazy Evaluation

- Lazy evaluation (non-strict evaluation) evaluates the expression only if needed.
  - Haskell is lazy, as the following works

    ```
    length [2+1, 3*2, 1/0, 5-4]
    ```

  - C++ is eager, but the following works

    ```
    template <typename... Args>
    void mySize(Args... args) {
      cout << sizeof...(args) << endl;
    }
    mySize("Rainer",1/0);
    ```

- Advantages:
  - Saving time and memory usage
  - Working with infinite data structures

Lazy Evaluation

- Examples:

```
successor i= i: (successor (i+1))
take 5 ( successor 10 )                   // [10,11,12,13,14]

odds= takeWhile (< 1000) . filter odd . map (^2)
[1..]= [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15 ... Control -C
odds [1..]                                // [1,9,25, … , 841,961]
```

- Special case: short circuit evaluation

```
if ( true or (1/0) )cout << "short circuit evaluation in C++\n";
```

What's missing?

- List comprehension:
  - Syntactic sugar of the sweetest kind with map and filter
  - Examples:

```
[(s,len(s)) for s in ["Only","for"]] # [('Only', 4), ('for', 3)]
[i*i for i in range(11) if i%2 == 0] # [0,4,16,36,64,100]
```

- Function composition:
  - Programming with LEGO bricks
  - Examples:

```
(reverse . sort)[10,2,8,1,9,5,3,6,4,7]-- [10,9,8,7,6,5,4,3,2,1]


theLongestTitle= head . reverse . sortBy(comparing length) .
  filter isTitle
theLongestTitle words("A Sentence Full Of Titles.")
```

➜ Result: "Sentence"

Functional Programming in C++11

science + computing

A Bull Group Company

Vielen Dank für Ihre Aufmerksamkeit.

Rainer Grimm

science + computing ag

www.science-computing.de

phone +49 7071 9457-253

r.grimm@science-computing.de